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CRACK FORMATION IN A CLAY SEMIFINISHED PRODUCT

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The method of investigating the crack resistance of a clay semifinished product during drying was examined. A safe duration of drying for articles of complex shape by plotting the diagram of the maximum possible moisture removal as a function of the form factors (reduced thicknesses) of simple parts of the article was proposed. The method was tested on samples of the investigated clay and industrial brick paste.

Manufacturers of construction ceramics have always focused special attention on drying processes, since drying occupies a significant part of the time in manufacturing any article. The necessity of rapidly optimizing the drying conditions is due to the variety of shapes of the ceramic ware used in current construction. Reducing the drying time is possible when many parameters (primarily the drying properties of the paste, then the moisture content, temperature, and heat carrier exchange rate) are optimized or efficient drying methods are used (microwave drying, drying with an electric current, etc.). The equipment for effective methods of drying construction materials, where thermal diffusion is directed to the surface of the article, is still not widely used, so that manufacturers only have one backup for increasing the drying rate — improving the drying properties of the paste by adding different kinds of additives that usually reduce the hydrophilicity of the paste.

One method of reducing the drying time and decreasing cracking of the semifinished product in industrial conditions is to determine the safe drying conditions. Nevertheless, it is very difficult to obtain a defect-free semifinished product, especially in changing from production of articles of one shape to another shape.

The effect of the reduced form factor (ratio of the volume of an article to the surface area) and maximum possible moisture removal on the crack resistance of the ceramic ware during drying is examined here.

The problems of drying clay-based construction articles were basically examined in studies in the 1940s-1970s, but questions concerning the effect of the shape of the article on drying have been touched upon very little [1, 2]. The concrete quantitative characteristics of the effect of the reduced form factor on drying are mentioned by A. A. Shumilin and A. I. Avgustinik [3, 4]. They proposed an exponential dependence of moisture removal m on the form factor of the article δ_V:

$$m = C\,\delta_V^n,$$

where C and n are coefficients, determined experimentally.

The effect of the shape of the semifinished product on the crack resistance can be explained by two factors. First, in drying, different defects can appear in the molding stage. Specific defects are characteristic of each molding method. For plastic molding, these are defects related to texture formation — sections of the structure with directional orientation. Second, in drying the semifinished product, new defects can form due to nonuniform shrinkage of different sections. The drying defects subsequently appear during firing of the articles.

Two pastes were selected for studying crack formation: clay from Levzhensk deposit and industrial paste from the Ruzaev Ceramics Ltd. brick works, made from this raw material. The following characteristics of the raw material were determined first: phase composition, plastic strength, optimum molding moisture content, air shrinkage, and sensitivity to drying [5].

The phase composition of the clay was determined by petrographic and x-ray diffraction analysis. Montmorillonite and kaolinite with a particle size of less than 2 μm were the basic clay-forming minerals. The kaolinite content did not exceed 7%, the quartz and feldspar rock (albite) content did not exceed 35 – 40%, and the limestone constituent was 7 – 8%.

The investigated clay belongs to the class of moderately plastic clays (plasticity number of 14). Determination of the binding power of the clay showed that in addition of 40% grog, the paste remained moderately plastic (plasticity num-

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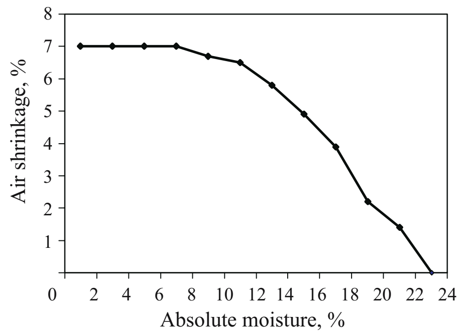

Fig. 1. Air shrinkage $\Delta l/l_0$ as a function of absolute moisture content W_{abs} during drying.

ber of 7). The optimum molding moisture content of the paste without addition of grogs, established with a Rebinder conical plastometer, was 23%.

The drying sensitivity coefficient, determined by the Chizhskii and Nosova methods, is considered the basic criterion of defect-free drying of a semifinished product [5]. The drying sensitivity coefficient was calculated with the Chizhskii method (Fig. 1) and was equal to 1.03; as a consequence, the investigated paste belongs to the low-sensitivity class.

Crack formation was investigated in samples in the form of slabs prepared by plastic molding at the optimum molding moisture content and on individual fragments of heat-efficient ceramic stone that differed in shape and drying conditions (Fig. 2). Several drying regimes were tested: in natural conditions at 20±2°C and forced-air drying at 60, 70, and 80°C.

After drying in natural conditions, no cracks were found visually in the samples. Intensive shrinkage occurred for 10 – 20 h (Fig. 3*a*).

Since the clay paste belongs to the group of pastes with low drying sensitivity, drying was subsequently conducted at temperatures from 60 to 80°C. The shrinkage was most intensive for 1 – 1.5 h (Fig. 3*b*). Cracking of some samples was also observed at this time.

The finished articles were also tested in factory conditions in industrial drying regimes.

The "safe" and "dangerous" regions of drying conditions and the dependence of critical moisture removal on the reduced form factor were established for samples of different size and shape molded from each paste (Fig. 4).

To increase the range of values of the reduced form factor, some of these samples were insulated with a thin polyethylene film. The necessary measures were also taken to prevent frame cracks in the samples due to slowing of shrinkage of the support material.

The boundary between regions of "dangerous" and "safe" moisture removal is not always clear [6]. Several samples in the shape of a rectangular slab made from clay from the Lenzhensk deposit and dried in the region of "safe" conditions also cracked (see Fig. 4*a*). As a consequence, the dependence of the maximum possible moisture removal on the reduced form factor cannot be a reliable reference point for describing the behavior of articles of different shapes during drying.

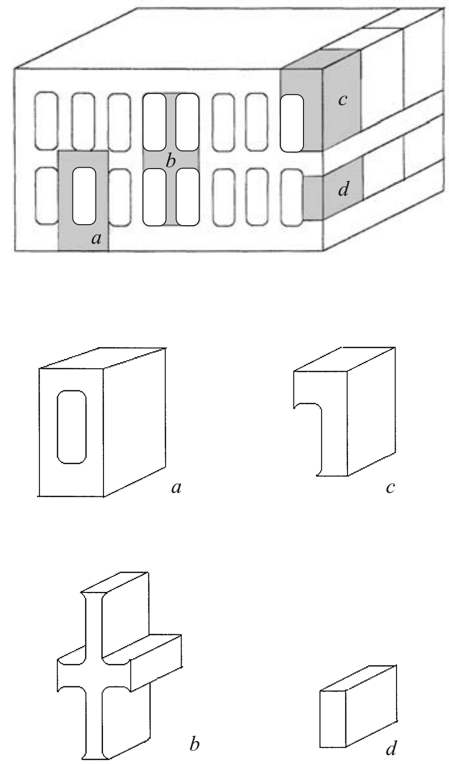

Fig. 2. Shape of samples.

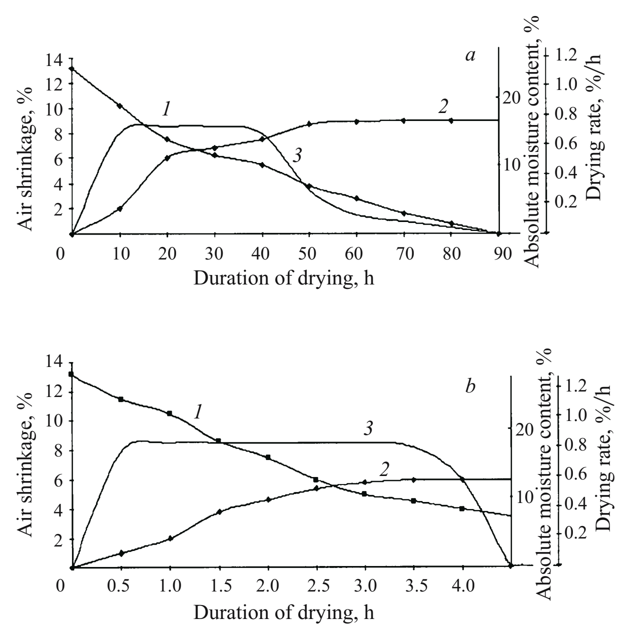

Fig. 3. Drying in natural conditions at 20°C (*a*) and in a laboratory desiccator at 80°C (*b*): *1*) absolute moisture content; *2*) air shrinkage; *3*) drying rate.

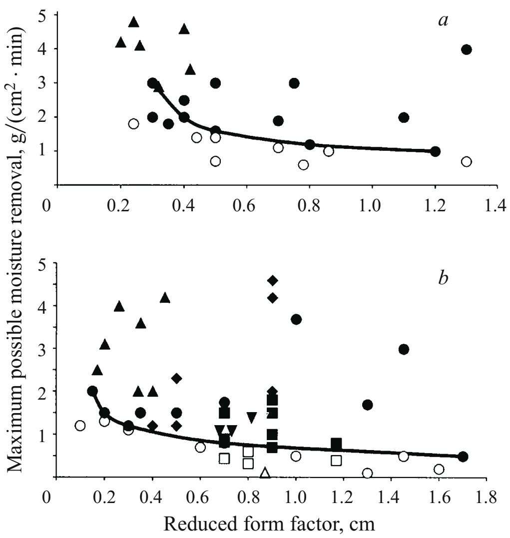

Fig. 4. Crack resistance of samples of the investigated clay (*a*) and industrial paste (*b*): ∗) moisture removed from samples in which cracks formed; ○) moisture removed from samples in which no cracks formed; ▲) moisture removed from parts of samples in which cracks formed; ■) moisture removed from samples of complex shapes in which cracks formed; □) moisture removed from samples of complex shapes in which no cracks formed; ◆) moisture removed from parts of samples of complex shapes in which cracks formed; △) moisture removed from whole industrial articles (with and without cracks); ▼) moisture removed from parts of industrial articles in which cracks formed.

For plotting a more correct curve, slab-shaped samples were divided into parts in which the drying conditions and thermal stress distribution clearly differed (Fig. 5).

In comparing the parts of the divided sample, we can say that parts 1, 3, 7, and 9 are identical, like parts 2, 4, 6, and 8 — they have the same area and form factor, respectively. The maximum possible moisture removal from the individual parts of the samples was calculated and the values were plotted in a diagram. For the parts where cracks formed, moisture removal was in the region of forbidden drying regimes.

TABLE 1

Sample*	Level in drying chamber A	Residence time in chamber, min	Maximum possible moisture removal, 1000 g/(cm^2 · min)	Site of cracks
1	Lower	180	0.019	No cracks
2	Middle	180	0.020	Same
3	Upper	180	0.030	″
4	Lower	600	0.030	″
5	Middle	600	0.042	″
6	Upper	600	0.050	″
7	Lower	1620	0.100	″
8	Middle	1620	0.120	″
9	Upper	1620	0.116	Along scoop and header parts, in corners

* The overall form factor was 0.87 cm in all cases.

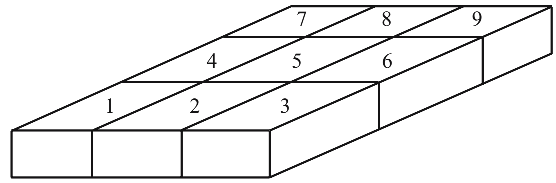

Fig. 5. Arbitrary division of a slab sample into parts.

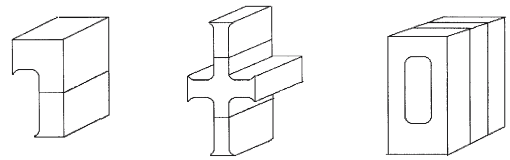

Fig. 6. Breakdown of samples of complex shapes.

Samples of industrial paste were also prepared to obtain heat-efficient ceramic stone and the dependence of the acceptable drying intensity on the reduced form factor was determined for samples of simple shapes. The overall picture of the behavior of this paste during drying at different temperatures and correspondingly, for different maximum possible moisture removal is shown in Fig. 4*b*. To refine and more precisely describe the samples with cracks, as for the first case, the samples were arbitrarily divided into simple parts, moisture removal from these parts was calculated, and their coordinates were entered in Fig. 4*b*.

After obtaining the overall dependence of the acceptable drying intensity on the reduced form factor for samples of simple shape, samples of more complex shape (heat-efficient ceramic stone parts, see Fig. 2) were investigated. The reduced form factor and maximum possible moisture removal were calculated and the coordinates obtained were entered in Fig. 4*b*. Samples of complex shape also obey the previously established dependence. For verification, these samples were divided into the simplest parts (Fig. 6), for which the coordinates were calculated and plotted in the same diagram.

The dependence of the acceptable drying intensity in industrial conditions on the reduced form factor of heat-efficient ceramic stone measuring 250 × 120 × 138 mm was obtained (Tables 1 and 2), and the calculated coordinates were plotted in Fig. 4*b*. It was assumed that the data corresponding to the performance values of the intensity of moisture removal are slightly understated for the articles, since in industrial conditions, to avoid underdrying and a large drop in the critical moisture content inside the articles, the duration of the first drying period was intentionally increased. For a complete picture of the dependence, the articles with cracks were arbitrarily divided into known parts (see Fig. 2), and the

moisture removal values for them are shown in Fig. 4*b* in the form of points.

To determine the safe drying conditions, the dependences of the duration of defect-free drying τ or the maximum safe moisture removal m with the determining size of the article — reduced form factor f — were established (Fig. 7). The dependences differed in the region of high form factor values.

These dependences can be analytically written as follows:

for samples of simple shape made from Levzhinskoe deposit clay

$$m_1 = 1.06 f^{-0.76};$$

$$\tau_1 = 0.31 f^{0.86};$$

for samples of simple shape from industrial paste

$$m_2 = 0.66 f^{-0.55};$$

$$\tau_2 = 0.26 f^{0.90}.$$

In analyzing the characteristics obtained, we find that the samples with approximately the same general form factor but different geometric characteristics behave differently during drying. By arbitrarily dividing these articles into constituent parts and separately considering the form factors of these parts, we can obtain a clear picture — moisture removal from the part of the article where the crack appears is greater than the maximum acceptable value, and in the part where cracks are not formed, the moisture removal values are in the region of permitted drying regimes. The results obtained in industrial conditions obey the dependences established above.

For the articles made of Levzhensk clay, we found that moisture removal should not exceed 1.4 – 1.5 g/(cm^2 · min) for a form factor of the samples and their characteristic parts of 0.2 – 0.7 cm, and should be within the limits of up to

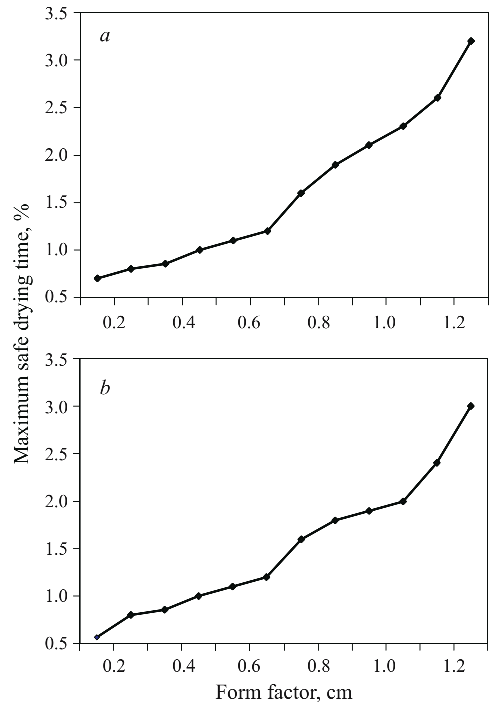

Fig. 7. Maximum safe drying time as a function of form factor of samples from the clay (*a*) and industrial paste (*b*).

1 g/(cm^2 · min) for articles made of the same paste with a minimum form factor of 0.7 cm. The samples from industrial paste with a form factor (including their characteristic parts) of 0.1 – 0.7 can safely be dried at moisture removal of 0.7 – 1.2 g/(cm^2 · min). The samples with an overall form factor or a form factor of their characteristic parts greater than 0.7 require drying at maximum moisture removal of 0.6 g/(cm^2 · min).

In analyzing the character and position of the cracks in the slab-shaped samples, we note that the cracks were most frequently positioned in the second part or identical to it (see

TABLE 2

Sample*	Level in drying chamber B	Residence time in chamber, min	Form factor of article part, cm	Maximum possible moisture removal, 1000 g/(cm^2 · min)		Site of crack
				total	from article part	
1	Lower	180	0.7	0.090	1.02	On surface of bottom
2	Middle	180	0.7	0.120	1.10	In corners and center
3	Upper	180	0.8	0.200	1.30	Along scoop part
4	Lower	600	0.7	0.050	0.45	On surface of bottom
5	Middle	600	0.7	0.060	0.60	In corners and center
6	Upper	600	0.8	0.078	0.78	Along scoop part
7	Lower	1620	0.7	0.140	0.90	Decrease in number of cracks
8	Middle	1620	0.7	0.240	1.20	Same
9	Upper	1620	0.8	0.160	1.23	″

* The overall form factor was 0.87 cm in all cases.

Fig. 5). This is because moisture removal from these parts during drying was greater than the acceptable safe value. In drying articles of this shape, the regimes must be calculated and selected relative to the drying regimes for this part.

It was found for samples of complex shape (see Fig. 2) that moisture removal in defect-free drying should be below 0.9 g/(cm^2 · min) for sample *c*, 0.4 and less for sample *b* in the same conditions, and below 0.6 g/(cm^2 · min) for sample *a*. Since these parts were considered as constituent parts of heat-efficient ceramic stone, we can conclude that part *b* is the most dangerous part, and the regime for drying the entire article should be selected for it.

In comparing the results of the studies with the test results in industrial conditions, we note that moisture removal from the parts of articles in which cracks were formed were higher than the acceptable values for defect-free drying. The dependence of the maximum safe moisture removal on the reduced form factor thus allows predicting the appearance and site of cracks.

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